The form factors of $\omega\pi^0$ and $\pi^+\pi^-$ at $\psi(2S)$

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The measurements of $\psi(2S) \to \omega\pi^0$ and $\psi(2S) \to \pi^+\pi^-$ in e^+e^- experiments are examined. It is found that the non-resonance virtual photon annihilation gives large contributions to the observed cross sections of these two processes. By including this contribution, the form factors and branching fractions of these two decay modes are revised.

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1. Introduction

Since its discovery, a large amount of $\psi(2S)$ data has been collected. The latest comes from BES [1]. This has led to detailed analysis of the interference pattern between the strong and the electromagnetic interactions in $\psi(2S)$ decays [2]. In such analysis, the electromagnetic decay modes such as $\omega\pi^0$ and $\pi^+\pi^-$ are of particular importance [2,3].

Up to now, the most precise measurements of the $\psi(2S)$ decays are by e^+e^- colliding experiments, where the production of $\psi(2S)$ is accompanied by

$$e^+e^- \to \gamma^* \to hadrons,$$

in which e^+e^- pair annihilates into a virtual photon without going through the intermediate resonance state. So the experimentally measured $\psi(2S) \to \omega\pi^0$ and $\psi(2S) \to \pi^+\pi^-$ processes are parallel to $\psi(2S) \to \mu^+\mu^-$ in the way that there are two Feynman diagrams: one is the $\psi(2S)$ and the other is the one-photon annihilation, as shown in Fig. 1. There are three terms in the cross section: $\psi(2S)$ resonance, one-photon annihilation and their interference. Unlike $\mu^+\mu^-$ pair which couples to virtual photon by QED fine structure constant, the couplings of $\omega\pi^0$ and $\pi^+\pi^-$ to virtual photon are by energy-dependent form factors

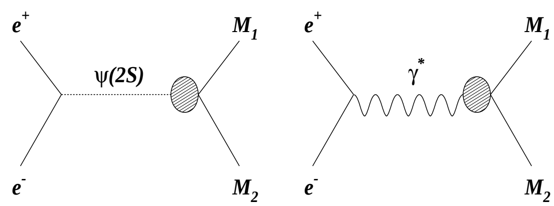

Figure 1. Feynman diagrams for $e^+e^- \to M_1 + M_2$ near $\psi(2S)$.

which are to be determined by experiments. By scanning around the $\psi(2S)$ peak, Γ_{ee} and $\Gamma_{\mu\mu}$ are determined from fitting the resonance shape with the theoretical curve, which includes the one-photon annihilation term and interference [4]. On the contrary, $\Gamma_{\omega\pi^0}$ and $\Gamma_{\pi^+\pi^-}$, due to their small branching fractions, are acquired from data collected on top of the resonance. The contributions from the one-photon annihilation and the interference are not subtracted.

In this work, the measurements of the $\omega\pi^0$ and $\pi^+\pi^-$ form factors at $\psi(2S)$ resonance by e^+e^- colliding experiments are examined. First, not only the $\psi(2S)$ resonance, but also the one-photon annihilation propagator are included in the experimentally observed cross section, which takes into account the initial state radiation and the finite energy resolution of the e^+e^- colliders. Next it is demonstrated that for current

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measurements, the one-photon annihilation contributes a large share to the observed cross sections of these two processes, and this leads to significant revision of the form factors of $\omega\pi^0$ and $\pi^+\pi^-$ and their branching fractions in $\psi(2S)$ decays. Finally, it is pointed out that the data off the $\psi(2S)$ resonance must be collected to study the one-photon annihilation process in order to get the complete information on $\psi(2S) \to \omega\pi^0$ and $\psi(2S) \to \pi^+\pi^-$ decays.

2. The experimentally observed cross section

The resonance part of the cross sections for $e^+e^- \to \psi(2S) \to \omega\pi^0$ and $e^+e^- \to \psi(2S) \to \pi^+\pi^-$, in the Born order, are expressed by the Breit-Wigner formula

$$\sigma_{Born}(s) = \frac{12\pi\Gamma_{ee}\Gamma_f}{(s-M^2)^2+\Gamma_t^2M^2}.$$

Here $\sqrt{s}$ is the center of mass energy; M and Γ_t are the mass and the total width of $\psi(2S)$; Γ_{ee} is the partial width to e^+e^-, and Γ_f ($f = \omega\pi^0$, $\pi^+\pi^-$) is the partial width to the final state f, which are related to Γ_{ee} and the corresponding form factors :

$$\Gamma_{\omega\pi^0} = \frac{\Gamma_{ee}q^3_{\omega\pi^0}}{m_{\psi(2S)}}|\mathcal{F}_{\omega\pi^0}(m^2_{\psi(2S)})|^2, \qquad (1)$$

and

$$\Gamma_{\pi^+\pi^-} = 2\Gamma_{ee}\left(\frac{q_{\pi^+\pi^-}}{m_{\psi(2S)}}\right)^3|\mathcal{F}_{\pi^+\pi^-}(m^2_{\psi(2S)})|^2. \qquad (2)$$

Here $q_{\omega\pi^0}$ is the momentum of either ω or π^0 in the $\omega\pi^0$ decay, $q_{\pi^+\pi^-}$ is the momentum of π in the $\pi^+\pi^-$ decay. $\mathcal{F}_{\omega\pi^0}(s)$ and $\mathcal{F}_{\pi^+\pi^-}(s)$ are the form factors of $\omega\pi^0$ and $\pi^+\pi^-$, respectively.

For the experimentally observed cross sections of $e^+e^- \to \omega\pi^0$ and $e^+e^- \to \pi^+\pi^-$ at $\psi(2S)$ peak, the direct one-photon annihilation term and an interference term must be added:

$$\sigma_{Born}(s) = \frac{4\pi\alpha^2}{s^{3/2}}[1+2\Re B(s)+|B(s)|^2]|\mathcal{F}_f(s)|^2\mathcal{P}_f(s), \qquad (3)$$

with

$$B(s) = \frac{3\sqrt{s}\Gamma_{ee}/\alpha}{s-M^2+iM\Gamma_t}, \qquad (4)$$

where α is the QED fine structure constant, and

$$\mathcal{P}_{\omega\pi^0}(s) = \frac{1}{3}q^3_{\omega\pi^0},$$

$$\mathcal{P}_{\pi^+\pi^-}(s) = \frac{2}{3s}q^3_{\pi^+\pi^-}.$$

More generally, there could be a phase between the one-photon and $\psi(2S)$ propagators, then instead of Eq. (4), one has

$$B(s) = \frac{3\sqrt{s}\Gamma_{ee}/\alpha}{s-M^2+iM\Gamma_t}e^{i\phi}, \qquad (5)$$

where ϕ is the phase between the two propagators. In the following analysis, both Eq. (4) and (5) are considered.

In e^+e^- collision, the Born order cross section is modified by the initial state radiation in the way [5]

$$\sigma_{r.c.}(s) = \int_0^{x_m} dxF(x,s)\frac{\sigma_{Born}(s(1-x))}{|1-\Pi(s(1-x))|^2}, \qquad (6)$$

where $x_m = 1 - s'/s$. $F(x,s)$ has been calculated to an accuracy of 0.1% [5–7] and $\Pi(s)$ is the vacuum polarization factor. In the upper limit of the integration, $\sqrt{s'}$ is the experimentally required minimum invariant mass of the final particles. In this work, $x_m = 0.2$ is used which corresponds to invariant mass cut of 3.3 GeV.

By convention, Γ_{ee} has the QED vacuum polarization in its definition [8,9]. Here it is natural to extend this convention to the partial widths of other pure electromagnetic decays. By using Eq. (1) and (2) to relate $\Gamma_{\omega\pi^0}$ and $\Gamma_{\pi^+\pi^-}$ with Γ_{ee}, these partial widths are experimentally measured ones with vacuum polarization implicitly included in their definitions.

The e^+e^- colliders have finite energy resolution which is much wider than the intrinsic width of $\psi(2S)$. Such energy resolution is usually a Gaussian distribution:

$$G(W,W') = \frac{1}{\sqrt{2\pi}\Delta}e^{-\frac{(W-W')^2}{2\Delta^2}},$$

where $W=\sqrt{s}$ and Δ, a function of the energy, is the standard deviation of the Gaussian distribution. The experimentally measured cross section

is the radiative corrected cross section folded with the energy resolution function

$$\sigma_{exp}(W) = \int_0^\infty dW' \sigma_{r.c.}(W') G(W', W). \qquad (7)$$

With the currently available $\psi(2S)$ parameters $M = 3.68596$ GeV, $\Gamma_{ee} = 2.19$ keV, $\Gamma_t = 300$ keV [10], on a collider with $\Delta = 1.3$ MeV, the maximum total cross section is 640 nb; while on a collider with $\Delta = 2.0$ MeV, the maximum total cross section is 442 nb[†].

3. $\omega\pi^0$ and $\pi^+\pi^-$ form factors measured at $\psi(2S)$

The decay $\psi(2S) \to \omega\pi^0$ is reported by BES to have a branching fraction of $(3.8 \pm 1.7 \pm 1.1) \times 10^{-5}$ [13]; and $\psi(2S) \to \pi^+\pi^-$ is reported by the same group to have a branching fraction of $(8.4 \pm 5.5^{+1.6}_{-3.5}) \times 10^{-6}$ [14]. With the energy resolution of BEPC/BES, these values actually mean that the measured cross section of $e^+e^- \to \omega\pi^0$ at $\psi(2S)$ is $(2.4 \pm 1.3) \times 10^{-2}$ nb while for $e^+e^- \to \pi^+\pi^-$ it is $(5.4^{+3.7}_{-4.2}) \times 10^{-3}$ nb. An earlier result of $\psi(2S) \to \pi^+\pi^-$ by DASP gives a branching fraction of $(8 \pm 5) \times 10^{-5}$ [15]. With the energy resolution of DORIS/DASP, this means that the measured cross section at $\psi(2S)$ is $(3.5 \pm 2.2) \times 10^{-2}$ nb.

Using these measured cross sections, together with Eq. (3), (4), (6) and (7), the form factors can be estimated. In the calculation of radiative correction, the upper limit of the integration in Eq. (6) used here requires the knowledge of these form factors between 3.3 GeV and $\psi(2S)$ mass. For this purpose, the following s dependences are assumed:

$$|\mathcal{F}_{\omega\pi^0}(s)| \propto \frac{1}{s^2},$$

and

$$|\mathcal{F}_{\pi^+\pi^-}(s)| \propto \frac{1}{s},$$

[†]Different accelerator has different energy resolution, and their difference is sometimes large [11]. Here $\Delta = 1.3$ MeV corresponds to the energy resolution of BEPC/BES [12] at the $\psi(2S)$ energy region; and $\Delta = 2.0$ MeV corresponds to DORIS/DASP at the same energy. Throughout this paper, these values of the parameters are used for numerical calculation.

which are derived from QCD [3].

First assume that in Eq. (3), $B(s)$ is expressed by Eq. (4). The $\omega\pi^0$ form factor is usually normalized to its value at $Q^2 = 0$ by using the crossed channel decay $\omega \to \gamma\pi^0$. With the BES measured $\omega\pi^0$ cross section at $\psi(2S)$,

$$\begin{aligned}
&\frac{|\mathcal{F}_{\omega\pi^0}(m^2_{\psi(2S)})|}{|\mathcal{F}_{\omega\pi^0}(0)|} \\
&= \sqrt{\frac{\alpha}{3}\left(\frac{P_\gamma}{P_\omega}\right)^3 \frac{m_{\psi(2S)}\Gamma(\psi(2S) \to \omega\pi^0)}{\Gamma(\omega \to \gamma\pi^0)\Gamma(\psi(2S) \to \mu^+\mu^-)}} \\
&= (1.6 \pm 0.4) \times 10^{-2},
\end{aligned}$$

where $P_\gamma(P_\omega)$ is the photon(ω) momentum in the $\omega(J/\psi)$ rest frame. This corresponds to the branching fraction

$$\mathcal{B}_0(\psi(2S) \to \omega\pi^0) = (1.6 \pm 0.9) \times 10^{-5}\ .$$

Similarly, with the BES measured $\pi^+\pi^-$ cross section,

$$|\mathcal{F}_{\pi^+\pi^-}(m^2_{\psi(2S)})| = (4.5^{+1.5}_{-1.7}) \times 10^{-2},$$

and

$$\mathcal{B}_0(\psi(2S) \to \pi^+\pi^-) = (3.5^{+2.3}_{-2.7}) \times 10^{-6}.$$

With DASP result,

$$|\mathcal{F}_{\pi^+\pi^-}(m^2_{\psi(2S)})| = 0.12 \pm 0.04,$$

and

$$\mathcal{B}_0(\psi(2S) \to \pi^+\pi^-) = (2.6 \pm 1.6) \times 10^{-5}.$$

In the above equations, $\mathcal{B}_0$ indicates the actual branching ratio of $\psi(2S)$ decays after continuum contribution being subtracted.

Next consider a possible phase between the two propagators, then instead of Eq. (4), Eq. (5) for $B(s)$ is used in Eq. (3) for the Born order cross section. With an extra parameter, the form factors vary in a range, depending on the phase. Then with BES result on $\omega\pi^0$,

$$(1.4 \pm 0.4) \times 10^{-2} \leq \frac{|\mathcal{F}_{\omega\pi^0}(m^2_{\psi(2S)})|}{|\mathcal{F}_{\omega\pi^0}(0)|} \leq (1.8 \pm 0.5) \times 10^{-2}$$

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and

$$(1.2 \pm 0.6) \times 10^{-5} \leq \mathcal{B}_0(\psi(2S) \to \omega\pi^0) \leq (2.1 \pm 1.1) \times 10^{-5}.$$

The lower or upper limit herein corresponds to $\phi = 90^\circ$ or -90° which leads to maximum constructive or destructive interference between the two propagators.

Similarly, with BES result on $\pi^+\pi^-$,

$$(3.9^{+1.3}_{-1.5}) \times 10^{-2} \leq |\mathcal{F}_{\pi^+\pi^-}(m^2_{\psi(2S)})| \leq (5.3^{+1.8}_{-2.1}) \times 10^{-2},$$

and

$$(2.7^{+1.8}_{-2.1}) \times 10^{-6} \leq \mathcal{B}_0(\psi(2S) \to \pi^+\pi^-) \leq (4.8^{+3.3}_{-3.7}) \times 10^{-6}.$$

With DASP measurement on $\pi^+\pi^-$,

$$(0.11 \pm 0.03) \leq |\mathcal{F}_{\pi^+\pi^-}(m^2_{\psi(2S)})| \leq (0.14 \pm 0.04),$$

and

$$(2.1 \pm 1.4) \times 10^{-5} \leq \mathcal{B}_0(\psi(2S) \to \pi^+\pi^-) \leq (3.3 \pm 2.1) \times 10^{-5}.$$

These form factors extracted from experimentally measured cross sections are to be compared with theoretical calculations. For $\omega\pi^0$, a phenomenological model [3] predicts

$$\frac{|\mathcal{F}_{\omega\pi^0}(s)|}{|\mathcal{F}_{\omega\pi^0}(0)|} = \frac{m^2_\rho M^2_{\rho'}}{(m^2_\rho - s)(M^2_{\rho'} - s)},$$

where m_ρ and $M_{\rho'}$ are the masses of $\rho(770)$ and $\rho(1450)$ respectively. It gives

$$\frac{|\mathcal{F}_{\omega\pi^0}(m^2_{\psi(2S)})|}{|\mathcal{F}_{\omega\pi^0}(0)|} = 8.7 \times 10^{-3},$$

which agrees within two standard deviation with the above revised result based on BES measurement.

For $\pi^+\pi^-$, the first order QCD calculation relates the meson form factor with the decay constant by [16]

$$|\mathcal{F}_{\pi^+\pi^-}(s)| = 16\pi\alpha_s(s)\frac{f^2_\pi}{s} .$$

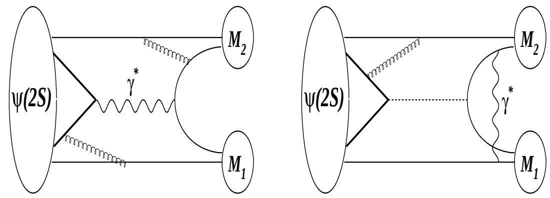

Figure 2. Nonvalence diagrams where $M_{1,2}$ represent two mesons.

Using $f_\pi = 0.093$GeV and $\alpha_s(M^2_{\psi(2S)}) = 0.25$, one gets

$$|\mathcal{F}_{\pi^+\pi^-}(M^2_{\psi(2S)})| = 8.0 \times 10^{-3}.$$

This is too small compared with the value extracted from the data above. There are also estimations by phenomenological models, e.g. in Ref. [17]. Most of the theoretical estimations do not exceed [3]

$$|\mathcal{F}_{\pi^+\pi^-}| \simeq \frac{0.5 \sim 0.6 \ \ \text{GeV}^2}{s} .$$

So the value extracted from the BES result is near the upper bound of the theoretical estimations.

The estimations of the forms factors in this section serve, to some extend, for illustrative purpose. The analysis of the data depends on more experimental details which will be discussed in the next section. Furthermore, if the nonvalence diagrams in Fig. 2 make important contributions [3], then Eq. (3) may not describe the process well. In order to determine the form factors at $\psi(2S)$ free of theoretical assumptions, it is essential to know the cross sections of these modes by one-photon annihilation process from experiments. This is done by collecting data near but off the resonance with comparable integrated luminosity as on top of the resonance. The experimentally measured one-photon annihilation cross sections of these modes are to be subtracted from the ones measured at $\psi(2S)$ to get the branching fractions and the form factors. With data both on and off resonance, one can compare the form factors at $\psi(2S)$ with those at the energy nearby, to test the importance of the nonvalence

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diagram. A more precise way is to scan the resonance shape and fit these partial widths with theoretical curves, as it is done for Γ_{ee} and $\Gamma_{\mu\mu}$ measurement. In this way, the possible phase between the two propagators could be explored. To accumulate sufficient integrated luminosity at each energy point, this has to be done on the high luminosity colliders, such as the upcoming CESR-c/CLEO-c [18] and BEPC-II/BES-III [19].

4. The dependence of the measurement on the experimental details

In this section, the dependence of the measurement on the experimental details are discussed.

One important feature is that in the total measured cross section, the resonance part depends sensitively on the energy spread of the collider. The larger the energy spread, the smaller the resonance part of the cross section. On the other hand, such energy spread hardly affects the one-photon annihilation part of the observed cross section, which is a smooth function of c.m. energy $\sqrt{s}$. For example, using Eq. (3) and (4) for the Born order cross section, for BEPC/BES ($\Delta = 1.3$ MeV) in $e^+e^- \to \omega\pi^0$ process, only 40.9% of the observed cross section comes from $\psi(2S)$; the other 60.4% is from the one-photon continuum and there is -1.3% negative contribution from interference. For $e^+e^- \to \pi^+\pi^-$ process, the percentages are 41.4%, 60.0% and -1.4%. There are colliders with larger energy spread. In such cases the percentage of the resonance part in the observed cross section is smaller. For DORIS/DASP ($\Delta = 2.0$ MeV), these percentages are 32.7%, 68.5% and -1.2% for $\pi^+\pi^-$.

Another important feature is that the one-photon annihilation term, with radiative correction, depends sensitively on the upper limit of the integration x_m in Eq. (6), which means the invariant mass cut in the event selection. In contrast, the resonance part hardly changes with x_m as long as $x_m \gg \Gamma_t/M$ due to the behavior of the Breit-Wigner formula, so it is virtually independent of the invariant mass cut under practical event selection criteria. In fact, the tighter cuts on the invariant mass of the final hadrons, which corresponds to smaller x_m, the smaller the one-photon annihilation part of the observed cross section. In the calculations of this work, the value of $x_m = 0.2$ is used, which means a lower cut of $\omega\pi^0$ or $\pi^+\pi^-$ invariant mass at $\sqrt{1-0.2}M_{\psi(2S)} = 3.3$ GeV. Such cut or its equivalence is usually imposed in the event selection to separate the $\psi(2S)$ daughter particles from J/ψ's. In the actual situation, the event selection criteria is far more complicated than a simple cut on the invariant mass. The quantitative analysis of the data requires the Monte Carlo simulation.

The third feature is that the treatment of the one-photon annihilation term is sensitive to the energy on which the data is taken. Small changes of the energy lead to rapid variation of the resonance and the interference term. Experiments naturally tend to collect resonance data at the energy which yields the maximum inclusive hadron cross section. This energy is not the nominal resonance mass, but somewhat higher. Nor does it necessarily coincide with the maximum cross section of each exclusive mode, due to the interference effect. For example, with energy resolution $\Delta = 1.3$ MeV, the maximum cross sections of inclusive hadrons and $\omega\pi^0$ mode happen at energies which are 0.14 MeV and 0.81MeV above the nominal $\psi(2S)$ mass respectively. At the energy which yields the maximum cross section of the inclusive hadrons, the $\omega\pi^0$ mode reaches only 95% of its own maximum value; While at the energy which yields the maximum $\omega\pi^0$ cross section, the percentages of resonance, one-photon annihilation and interference are 34.8%, 57.3% and +7.8%, respectively.

5. Conclusion

The above analyses and estimations show that possibly a large fraction of the observed cross sections of $e^+e^- \to \omega\pi^0$ and $e^+e^- \to \pi^+\pi^-$ come from the direct one-photon annihilation instead of $\psi(2S)$ decays. This contribution should be taken into account, in order to obtain the correct branching fractions of $\psi(2S) \to \omega\pi^0$ and $\psi(2S) \to \pi^+\pi^-$. Experimentally, it is necessary to collect data of comparable integrated luminosity near but off the $\psi(2S)$ peak. In this way, the cross sections from the direct one-photon an-

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nihilation could be measured for $e^+e^- \to \omega\pi^0$ and $e^+e^- \to \pi^+\pi^-$. They can be subtracted in the determination of the branching fractions and form factors. However, in this way, the possible phase between the two propagators is left unknown. A more precise method is to scan the resonance shape and fit $\Gamma_{\omega\pi^0}$ and $\Gamma_{\pi^+\pi^-}$ like it is done for measuring Γ_{ee} and $\Gamma_{\mu\mu}$. With this scheme, the existence of an extra phase between the two propagators, as indicated in Eq. (5), could also be checked.

In the future high luminosity experiments, like CLEO-c [18] and BES-III [19], as the accuracy goes much higher, not only the one-photon annihilation part of the cross section must be treated precisely, the interference term could also become relevant to the measurements.

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